# METHODS AND APPARATUS FOR IMPLEMENTING MULTI-TONE RECEIVERS

## Field of the Invention

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The present invention relates to communications systems and, more particular, to methods and apparatus for implementing multi-tone receivers, e.g., orthogonal frequency division multiplexed (OFDM) signal receivers.

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## Background

As people become more mobile, the number of portable devices, e.g., notebook computers, personal data assistants, cell phones, etc., continues to increase. 15 The use of wireless communications techniques enables modern portable devices to receive and transmit data from various locations.

20 With recent advances in the Internet and other data services, users of portable devices are beginning to feel a need to receive and transmit ever increasing amounts of data using wireless communications techniques.

25 In wireless communications a data signal, e.g., a series of symbols, is frequently modulated on a carrier signal, e.g., a carrier tone, having a particular carrier or tone frequency. In order to increase the amount of data that can be transmitted in a given period of time, a

plurality of different carriers may be used to transmit data, e.g., symbols, in parallel. This results in the broadcasting of what is known as a multi-tone signal. When multi-tone signals are used, the bandwidth of the
5    system becomes a function of the number of carrier signals in the multi-tone signal. An OFDM signal is one particular type of multi-tone signal.

As the result of the transmission of a signal
10    through a communications channel and the processing of the received signal, e.g., by a tuner and other circuitry, the transmitted signal may be distorted. For example, the communications channel may introduce amplitude and/or phase distortions. Tuners and other
15    receiver circuitry may introduce time varying phase distortions sometimes call phase jitter. Such signal distortions can make it difficult to recover transmitted data, e.g., symbols, from a received signal.

20    Communications channel distortions are difficult to avoid particularly in the case of over the air transmissions. Accordingly, attempts at addressing communications channel distortions have focused primarily on compensating for the introduced distortions at some
25    point in the receiver.

Phase jitter, in contrast to communications channel distortions, can be reduced or eliminated by using high quality circuits in the receiver.

Accordingly, attempts at addressing phase jitter have been focused on using better quality tuners and other circuits in a receiver than those which introduce unacceptable amounts of phase jitter.

While reducing phase jitter by using high quality receiver components can be effective, it has the disadvantage of requiring the use of high quality components which are usually more expensive than lower quality components, i.e., the components which introduce more phase jitter. In consumer applications, cost is often a major concern. Accordingly, from a cost perspective, in many applications the use of high quality tuners and other comparatively expensive circuitry can be undesirable.

In view of the above discussion, it should be apparent that there is a need for methods and apparatus for increasing the amount of phase jitter which can be tolerated in a receiver, e.g., a multi-tone signal receiver, thereby facilitating the use of relatively inexpensive tuners and/or other receiver circuitry. In addition, from a cost perspective, it is desirable that at least some methods and apparatus for enhancing a receiver's tolerance of phase jitter be relatively straight forward and inexpensive to implement.

## SUMMARY OF THE INVENTION

The present invention is directed to methods and apparatus for implementing multi-tone receiver circuitry, e.g., OFDM receivers. In particular, the invention is directed to reducing and/or eliminating the effect of phase jitter in a multi-tone receiver.

In accordance with the present invention, jitter compensation filtering is performed on a multi-tone signal, e.g., representing transmitted symbols, to reduce and/or eliminate the effect of phase jitter on the signal. The filtering operation may be performed following timing recovery and/or channel compensation processing operations, e.g., prior to demodulation.

To perform the jitter compensation filtering, a multi-tap filter, e.g., a programmable FIR filter, is used to process the received signal. The filter's tap weights are updated using at least one error estimation and/or error measurement technique. The received signal is reprocessed and the filter coefficients updated again. The filtering and filter updating steps are performed iteratively, e.g., for a preselected number of iterations and/or until some filter updating stop criterion are satisfied, e.g., the filtered signal ceases to improve from the use of the updated filter.

In one exemplary embodiment, the jitter compensation filter operates on a block of data. The block of data may include samples representing the symbols received on different carrier tones during the same symbol time. After a block of data is processed by the jitter compensation filter, the filter's tap weights are reset to their initial values before a new block of data is processed. The resetting of the filter tap weights reflects the fact that phase jitter may not correlate from block to block due to the time varying nature of the jitter.

Decision directed error measurements, pilot directed error measurements, and other non-decision directed error measurement techniques, e.g., constant modulus error measurement techniques are applied to the filtered signal to generate an error signal which can be used to update the jitter compensation filter's tap weights. The particular error measurement technique used at any given point of time is selected as a function of, e.g., whether a pilot symbol is being processed and/or whether a mean squared error generated from the decision directed error estimate is below a preselected threshold indicating that the decision directed error may be beneficial in updating the filter tap values.

The jitter compensation techniques of the present invention allow inexpensive tuners and/or other

receiver circuitry, having otherwise excessive phase noise, to be used in a multi-tone, e.g., OFDM, receiver.

5    Additional features, embodiments and benefits of the methods and apparatus of the present will be discussed below in the detailed description that follows.

## BRIEF DESCRIPTION OF THE DRAWINGS

10    Fig. 1 illustrates an OFDM receiver circuit.

Fig. 2 illustrates an ideal OFDM spectrum.

Fig. 3 is an expanded view of a portion of the
15   ideal OFDM spectrum illustrated in Fig. 2.

Fig. 4 illustrates an idealized jitter spectrum which may be encountered when processing an OFDM signal.

20    Fig. 5 illustrates the effect of the jitter illustrated in Fig. 4 on an OFDM spectrum such as that shown in Fig. 2.

Fig. 6 is an expanded view of a portion of the
25   jitter affected OFDM spectrum illustrated in Fig. 5.

Fig. 7 illustrates an OFDM receiver circuit which includes jitter compensation circuitry in accordance with the present invention.

Fig. 8 illustrates an exemplary jitter compensation filter which can be used in the OFDM receiver circuit shown in Fig. 7.

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Fig. 9 illustrates an exemplary filter cell which may be used to implement the jitter compensation filter of Fig. 8.

10          Figs. 10 and 11 illustrate exemplary error calculation circuits implemented in accordance with different embodiments of the present invention which can be used in the jitter compensation filter of Fig. 8.

15          Fig. 12 shows, in the form of a graph, a set of initial jitter compensation filter tap weights used in accordance with one exemplary embodiment of the present invention.

20          Fig. 13 is an exemplary OFDM output constellation before convergence of the jitter compensation filter tap weights used to filter the block of received samples representing the plotted symbols.

25          Fig. 14 illustrates a set of jitter compensation tap weights resulting after six iterations of the filter refinement process of the present invention.

Fig. 15 illustrates an exemplary output of the jitter compensation filter after updating the initial filter tap weights shown in Fig. 12 for a sixth time.

5    **DETAILED DESCRIPTION**

The present invention relates to methods and apparatus for implementing a multi-tone signal receiver, e.g., an OFDM signal receiver. In accordance with
10   various embodiments of the present invention, jitter compensation circuitry, e.g., a jitter compensation filter, is included as part of the signal receiver to increase the receiver's jitter tolerance as compared to receivers without such jitter compensation circuitry.
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Figure 1 shows a basic block diagram of an OFDM receiver circuit 100 which can be used as part of an OFDM demodulator. The receiver circuit 100 includes a resampling circuit 102 which may be implemented, e.g.,
20   using an A/D converter, a fast fourier transform (FFT) circuit 104, a parallel to serial converter (P/S) 106, a channel compensation circuit 108, a channel estimation circuit 110 and a timing recovery circuit 112 coupled together as illustrated in Fig. 1. The various circuits
25   illustrated in Fig. 1 can be implemented using known techniques. The resampling circuit 102 is responsible for sampling the received OFDM signal and generating digital samples therefrom as a function of signal timing information obtained from timing recovery circuit 112.

The digital samples are supplied to the FFT circuit 104 which performs a fast Fourier transform operation thereon. The digital samples corresponding to each sub-carrier signal of the received OFDM signal are supplied

5    in parallel to the parallel to serial converter circuit 106. The circuit 106 converts the parallel input into a serial data stream which is supplied to the channel compensation circuit 108. The channel compensation circuit 108 performs one or more signal processing

10   operations, e.g., filtering operations, designed to correct for signal distortions introduced by the communications channel from which the OFDM signal is received. The channel compensation circuit 108 uses channel information obtained from channel estimation

15   circuit 110 when performing channel compensation operations.

The OFDM receiver circuit 100 may, and in one embodiment is, followed by demodulator circuitry

20   including circuits for performing demapping, decoding and forward-error-correction functions.

Figure 2 is a diagram 200 an exemplary ideal OFDM spectrum, which comprises a number of carriers. The

25   vertical axis in Fig. 2 is a function of signal energy while the horizontal axis is a function of frequency. OFDM carrier tones are spaced one horizontal integer unit apart in the Fig. 2 illustration. Figure 3 is a diagram 300 which provides an expanded illustration of a portion

of the OFDM spectrum shown in Fig. 2.  In Fig. 3 it can
be seen that the energy of each OFDM carrier passes
through zero at the surrounding carriers' center
positions.

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Figure 4 is a diagram 400 showing an exemplary
jitter spectrum.  If a local oscillator used for
frequency conversion in the OFDM transmitter or receiver
is contaminated by phase noise, it will no longer be a
10   perfect sine wave, and therefore will have some finite
spectral width resulting in a spectrum such as that
illustrated in Fig. 4.  The phase noise contaminated
signal in Fig. 4 is in contrast to the impulse function
that would occur if a perfect sine wave were plotted on
15   the Fig. 4 chart.  When the output of an oscillator
having a signal such as that shown in Fig. 4 is mixed, or
multiplied, with the OFDM spectrum, it has the effect of
convolution in the frequency domain.

20   Figure 5 is a diagram 500 showing the
convolution of the exemplary jitter spectrum shown in
Fig. 4 with the exemplary ideal OFDM spectrum illustrated
in Fig. 1.  Figure 6 is a diagram 600 which shows an
expansion of a portion of the spectrum illustrated in
25   Figure 5.  In Fig. 6 it can be clearly seen that the
energy of each carrier now does not pass through zero at
the surrounding carriers' center positions as in the case
of the ideal OFDM spectrum shown in Figs. 2 and 3.  In

Fig. 6, the carriers are no longer purely orthogonal, thereby resulting in inter-carrier interference.

Fig. 7 illustrates an OFDM receiver circuit 700
5    implemented in accordance with the invention.  The circuit 700 includes a resampling circuit 102, FFT circuit 104, P/S circuit 106, channel compensation circuit 108, channel estimation circuit 110, and a timing recovery circuit 112 which are the same as, or similar
10   to, the like named circuits described above in regard to Fig. 1.  In addition to these elements, the OFDM receiver circuit 700 includes a jitter compensation circuit 702 implemented in accordance with the present invention. The jitter compensation circuit 702 receives as its
15   input, the output of the channel compensation circuit 108, e.g., a block of samples upon which channel compensation has been performed.  It also receives timing information from the timing recovery circuit 112.

The jitter compensation circuit 702 includes a
20   buffer 704, a jitter compensation filter 706, and an error calculation circuit 708 each of which receives timing information from timing recovery circuit 112.  In addition the compensation circuit 702 includes a filter update and output control circuit 712 and a latch 710.
25   The latch 710 has an enable input which is enabled by the filter update and output control circuit 712 when it determines that the filtering of the signal, e.g., block of samples received from the channel compensation circuit

108 during a symbol time period has undergone sufficient filtering. The output of the latch 710 serves as the output of the jitter compensation circuit 702 and is supplied, e.g., to subsequent demodulator circuitry.

5      The buffer 704 is used to receive and hold the output of the channel estimation compensation circuit 108 so that it can be repeatedly processed by the jitter compensation filter 706 prior to being output by the OFDM receiver circuit 700.

10      The jitter compensation filter 706 is used to reduce and/or remove intercarrier interference caused by random jitter, e.g., prior to demodulation. The jitter compensation filter 706 is particularly well suited to reducing and/or eliminating jitter caused by, e.g., tuner

15 phase noise. In order to allow the jitter compensation filter 702 to process a block of samples multiple times, the jitter compensation filter operates at a clock rate which is a multiple of the sampling rate used to initially generate the digital signal being processed.

20      The error calculation circuit 708, is coupled to, and receives as its input, the filtered samples output by the jitter compensation filter 706. The error calculation circuit 708 is used to calculate a filter coefficient update signal, e.g., in the form of an error

25 signal, used to adjust the jitter compensation filter's tap weights. After the filter taps are updated by the error signal, the data stored in the buffer 704 is

filtered again.  In this manner, the filter coefficients corresponding to the jitter compensation filter's taps are updated as part of an iterative process.

A fixed number of iterations, (e.g., filtering, error calculation and filter update cycles) may be set, or the iterations may be allowed to proceed until the system is deemed to have converged, e.g., at a stable jitter compensation filter output result.  The filter update and output control circuit 712 is responsible for determining, e.g., from the error signal and/or clock signals, when the selected filter output criteria have been satisfied.

Because phase jitter is generally uncorrelated from OFDM symbol to OFDM symbol, e.g., from FFT block to FFT block, in the exemplary embodiment a new filter solution is generated for each input block.  In a case where each symbol period is used to transmit a separate FFT block, the jitter compensation filter tap weights would be reset each symbol period.  The jitter compensation filter 706 acts as an equalizer.  The filter's taps may be set to an initial solution of, e.g., a unity center tap surrounded by zero taps, at the beginning of processing of each block of FFT values. This can be done by way of a reset signal, e.g., a latch enable and filter reset (LEFR) signal, generated by the filter update and output control circuit 712.  The LEFR signal used to reset the filter taps to their initial values is also used to enable the output latch 710.

The jitter compensation filter 706 can be
trained for a fixed number of iterations or the decision-
directed error or other metric can be examined to
determine when the compensation filter taps have
5    adequately converged at which point the latch 710 is
enabled and the jitter compensation tap weights reset for
processing the next block of symbol values.  The filter
update and output control circuit 712 is responsible for
performing this function.  The same signal, LEFR, which
10   stands for Latch Enable and Filter Reset, can be used to
enable the latch 710 and reset the tap weights in the
jitter compensation filter 706 to preselected, e.g.,
initial, values.  In one embodiment, the output control
circuit 712 enables the LEFR signal after a preselected
15   number of jitter compensation filter update cycles.  In
another embodiment, the LEFR signal is generated after
the filter update and output control circuit determines
from the error calculation circuit error output that the
error estimate has ceased to improve but is improving by
20   less than a preselected threshold amount with each
iteration.  After its assertion the filter update and
output control circuit de-asserts the LEFR signal so that
filter updating starting from the initial values filter
tap weight values may occur once again.

25       The jitter compensation filter 706 can, and in
some embodiments is, implemented as a finite impulse
response (FIR) filter with adaptable tap weights,
sometimes called filter coefficients.  An exemplary

jitter compensation filter 706 suitable for use in the
system 700 is shown in Figure 8.

In Fig. 8, the filter 706 is shown as having an
adder 806 and a plurality of coefficient cells 802, 802'
5    802'' arranged to form a sequence of N filter cells, each
cell corresponds to one filter tap.  The first filter
cell, 802, in the sequence of N filter cells receives as
its input the jitter compensation filter output.  A cell
output of the first filter cell 802 is coupled to the
10   cell input of the next filter cell 802', in the sequence
of N filter cells.  Thus, with the exception of the first
filter cell 802, the Nth filter cell in the sequence
receives its cell input from the cell output of the
preceding (N-1) filter cell.  The output of the last
15   filter cell (Nth) filter cell 802" in the sequence of N
filter cells goes unused since there is no subsequent
filter cell.

Each of the filter cells also receives, as an
input, error information generated by the error
20   calculation circuit 708.  The error information may be,
e.g., tap weight update information, which is used by the
filter cells to update their internal tap weight or
weights.  The tap weights may be reset to an initial
value after processing the block of data corresponding to
25   a symbol period by way of the LEFR signal which is used
as a reset signal.

Each of the N filter cells 802, 802', 802''
generates a cell product. The cell product from each
filter cell is supplied as an input to the adder 806.
The adder 806 sums the cell products output by each of
5  the N coefficient cells to generate the jitter
compensation filter's output signal. Thus, the output of
the jitter compensation filter 706 is the summation of
the outputs of the individual coefficient cells. As will
be discussed below, the jitter compensation filter output
10  signal is used by the error calculation circuit 708 to
generate the error information, used to update the jitter
compensation filter's tap weights to be used in the next
iteration of the filtering process.

A first exemplary jitter compensation
15  coefficient filter cell 802 is shown in Figure 9. The
filter cell 802 comprises a register 902, conjugate
circuit 904, a first multiplier 906, adaptive gain
circuit 908, adder 910, tap register 912 and a second
multiplier 914. The tap register 912 stores the filter
20  coefficient, also sometimes called tap weight, used by
the filter cell 802.

The shift register 902 is a delay element that
serves as part of the general delay-line structure of the
overall FIR jitter compensation filter 706. The output
25  of the register 902 is multiplied by the coefficient
value stored in tap register 912 thereby producing the
output, e.g., cell product, of the coefficient cell 802.

The tap value is updated after each filtering operation as a function of the received error signal (ERROR). In the Fig. 9 embodiment, the multiplier 906 multiplies the received error signal with the conjugate

5   of the value output by the shift register 902. The multiplier output value is then scaled by gain circuit 908 by an amount set within the circuit 908. The scaled multiplier output is supplied to a subtracting input of adder 910 which further receives, at an adding input, the

10  current value stored in tap register 912. The resulting corrected filter coefficient value, generated by subtracting the scaled multiplier output value from the current filter coefficient value, is stored in tap register 912 in time to be used during the next filtering

15  operation.

In the above described manner, the value of tap stored in register 912, is updated by subtracting, through an adder 910 a correction signal which is the product, scaled by an adaptation gain, of the error

20  signal received from the error calculation block and the conjugate of the data stored in shift register 902. This approach represents a least-mean-square (LMS) update technique. Other tap weight updating mechanisms may be employed instead of, or in addition to, the described LMS

25  update technique.

A first exemplary error calculation circuit 804 is shown in Figure 10. The error calculation circuit 804 comprises a slicer 1002, first and second summers 1004,

1018, a squaring circuit 1006, accumulator 1008, register 1010 comparator 1012, first multiplexer 1014, second multiplexer 1016 and a pilot information circuit 1020 which are coupled together as illustrated in Fig. 10.

5      During operation, an incoming signal, e.g., a block of samples representing symbols output by the jitter compensation filter, is subject to slicing by the slicer 1002. The difference, produced by summer 104 which subtracts the slicer output from an input symbol, 10   produces a decision-directed error. The decision-directed errors, e.g., one per received symbol, output by summer 1004 are squared and then summed by accumulator 1008. The accumulator 1008 produces an average error metric referred to as "MSE" for mean-squared error. At 15   the end of processing the symbols included within the current OFDM block being filtered, the register REG 1010 is clocked to store the resulting MSE value, and the accumulator 1008 is reset to zero to prepare for accumulating in the next iteration. Local reset control 20   1005 is responsible for generating the accumulator reset signal, e.g., from received timing information.

The first comparator 1012 is used to compare the output value REG of register 1010 to a threshold MSE_THRESHOLD, e.g., a value set at or prior to system 25   implementation. When it is determined that the value REG is below the threshold MSE_THRESHOLD, the signal being filtered is deemed to have converged sufficiently that decision-directed errors may be used beneficially in

updating the compensation filter tap weights and the output of the first comparator 1012 is asserted.

The select input of the first multiplexer MUX1 1014 causes the multiplexer to output the decision-directed error supplied to its first input when REG is asserted (1), e.g., the signal being processed has converged sufficiently for the decision directed error to be used reliably.  When the value of REG exceeds the MSE_THRESHOLD, indicating a high error rate, the signal being processed is deemed not to have converged sufficiently to the point where decision-directed errors can be used reliably in updating the compensation filter tap weights and the output of the first comparator 1012 will not be asserted (0) causing the first multiplexer 1014 to output the zero supplied to the first multiplexer's second input.  In the illustrated embodiment, the multiplexer MUX1 1014 multiplexes a zero error for use on signals with non-pilot carriers in the case where the signal being processed has not sufficiently converged for the decision directed error to be used to update the jitter filter tap values.

Pilot carriers are known carrier values that are often transmitted within an OFDM signal.  Since they are known values, a reliable pilot-directed error signal can be formed during the pilot times, e.g., the times at which a pilot symbol is being processed.  The pilot values are stored somewhere within the receiver and can be used for error determination purposes when a pilot

symbol is being processed. In the Fig 10 example, a PILOT INFO block 1020, which receives timing information, is shown as storing the pilot value information. However, since pilot information is used in the channel

5      estimation process, that information may alternatively be stored in the channel estimation block 110 and supplied to the error calculation circuit as needed.

The error calculation circuit 804 calculates a pilot directed error by using the second adder 1018 to

10     subtract the pilot symbol value from the received symbol value. The resulting pilot directed error is supplied to the second input of the second multiplexer 1016 while the decision director error (or zero error value) output by the first MUX1 1014 is supplied to the second

15     multiplexer's first input.

In accordance with the exemplary embodiment of the present invention illustrated in Fig. 10, when possible, pilot directed errors are used instead of decision directed errors to generate the error signal

20     used to update the jitter compensation filter tap values. The second multiplexer MUX2 1016 is used to control when a pilot directed error as opposed to a decision directed error will be used to update the jitter compensation filter 706.

25     The second multiplexer MUX2 1016 is used to control whether the decision directed error output by MUX1 1014 or the pilot directed error generated by summer

1018 is used as the error output signal. The select
signal used to determine the output of MUX2 1016 is a
pilot valid signal received as part of the timing
information. The pilot valid signal indicates a pilot
5     symbol is being processed and thus, when the pilot
directed error will be valid and should be used.

When pilot symbols are being processed, the
select signal supplied to multiplexer MUX2 1016 will be
asserted (1) causing the pilot director error signal to
10    be used as the error calculation circuit's error output
signal. However, during other times the select signal
will be de-asserted (0) resulting in the output of the
first MUX1 1014 being used as the error output signal of
the error calculation circuit 804.

15       As an alternative to declaring zero error when
the signal being filtered is noisy and pilot symbols are
not being processed, an error signal for the non-pilot
tones can be calculated via a non-decision-directed
method. Then when the MSE falls below some predefined
20    threshold, e.g., the MSE_THRESHOLD, the decision directed
error generated by the non-pilot tones can be used in
updating the jitter compensation filter 706.

Fig. 11 illustrates a second exemplary error
calculation circuit 804' which is similar to the circuit
25    804 shown in Fig. 10. The Fig. 11 circuit differs from
the Fig. 10 circuit in that it uses a non-decision
directed error calculation method when the decision

directed error and the pilot directed error values are
not used.

One non-decision-directed error calculation
method is the constant-modulus algorithm, which
5    calculates the error as

$$ERR = Z * (|Z|^2 - R_0^2),$$

where the modulus $R_0^2$ is defined as

$$R_0^2 = <|Z_{SL}|^4>/<|Z_{SL}|^2>,$$

where the averaging denoted by <> is over all of the
10   ideal ("sliced") constellation points $Z_{SL}$.

In the Fig. 11 embodiment, the error
calculation circuit 804' includes a constant modulus
error generation circuit 1102 which generates a constant
15   modulus error value from the received input but is
otherwise similar to the circuit 804.  The output of the
constant modulus error circuit 1102 is supplied to the
second input of the first MUX 1 1014 as opposed to a zero
which was supplied in the Fig. 10 embodiment.  As a
20   result, the constant modulus error signal will be used as
the error calculation circuit's output signal when the
decision directed error and the pilot directed errors are
not used.

In accordance with the present invention,
25   jitter compensation circuit operates at a rate which is

faster, e.g., at a clock rate several times the clock rate of the channel compensation circuit and various other OFDM receiver circuits. This allows the same signal, e.g., set or block of values, output by the channel compensation circuit to be processed several times by the jitter compensation circuit 702 before being output, e.g., to subsequent demodulator circuitry.

An alternative to operating the jitter compensation circuit at a clock rate several times the clock rate of the various other OFDM receiver circuits is to utilize parallel hardware: for example, multiple jitter compensation filters and error calculation circuits, such that the output of one circuit feeds into the subsequent circuit. This would introduce overall latency into the system, but reduce the processing speed, i.e., clock rate required.

In order to support reprocessing of the input signal multiple times the jitter compensation circuit includes a buffer 704 for storing the input signal. However, for this purpose, the signal may be stored within the parallel-to-serial converter (106), or possibly an alternate storage location following the channel compensation block.

In accordance with the present invention, each time the signal is run through the jitter compensation filter 706, the compensation filter taps are trained and

the output normally becomes more reliable as the filter taps converge to a good solution.

Jitter compensation filter refinement in the above describe manner can, in many cases, make a previously unusable signal usable. Thus, it allows the use of more inexpensive analog components (tuners) having a high amount of phase noise then would otherwise be acceptable.

Figure 12 shows the initial value of taps in an exemplary 51-tap jitter compensation filter. In the Fig. 12 example the 51-tap filter has a center tap initialized to one, and the other taps initialized to zero.

Figure 13 shows a constellation of 1024 symbols represented by the block of bits, i.e., the signal being processed by the jitter compensation circuitry, after a first pass, that is, without any jitter compensation.

Figure 14 shows a set of filter taps (in absolute value) resulting after six iterations of filter updating in accordance with the present invention.

Figure 15 shows the output of the jitter compensation filter 706 on the same exemplary signal which resulted in the Fig. 13 plot, after the sixth iteration of updating the jitter compensation filter. Note that the 16-QAM constellation points carried over the each of the OFDM carriers are now clearly

distinguishable, and hence the previously unrecoverable data is now recoverable as a result of the jitter compensation filtering of the present invention.

5          The methods and apparatus of the present invention have been described in the context of an OFDM receiver application which may be used, e.g., for wireless local area networks, multi-channel multipoint distribution systems (MMDS), or terrestrial broadcast

10     purposes, in order to allow inexpensive tuners, having otherwise excessive phase noise, to be used. While described in an OFDM embodiment, the methods and apparatus of the present invention are not limited to OFDM applications and can be used in other types of

15     receivers which process multi-tone signals. Furthermore, while described in terms of circuits, the elements which make up the apparatus of the present invention can be implemented as software modules which can be used to control a programmable processor to perform the described

20     signal processing operations. Accordingly, the present invention encompasses software as well as circuitry for implementing the above described methods.